ONR Graduate Traineeship Award

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LONG-TERM GOALS

The long term goals of this project are to investigate statistical models for signals propagating in long-range underwater channels and to design signal processing techniques to mitigate signal fluctuations due to random disturbances such as internal waves.

OBJECTIVES

At long ranges, broadband receptions consist of early ray-like arrivals and a finale that is best described in terms of the low order modes. The energetic low mode signals are more strongly affected by internal wave scattering than the ray arrivals. By focusing on the low order modes, this project seeks to develop a better understanding of internal wave effects. The first objective of this project is to derive range-dependent mode statistics from experimental data obtained during the SPICE04 and LOAPEX experiments. Using these statistics, the second objective is to develop a statistical model to describe the low mode signals as a function of range. The third objective of this project is to develop new robust signal processing techniques based on the derived random channel model.

APPROACH

To characterize internal wave effects on the modes, this project will use the extensive data sets of low-frequency receptions recorded as a part of the North Pacific Acoustic Laboratory (NPAL) project. Two specific experiments are particularly relevant for the current work. First, the Long Range Ocean Acoustic Propagation EXperiment (LOAPEX) conducted in 2004 provided a unique opportunity to measure low mode receptions at a series of ranges from 50 km to 3200 km. In addition to LOAPEX, the SPICE04 experiment included transmissions from a bottom-mounted source at Kauai to a receiving array at a range of 2400 km. This project will analyze the LOAPEX and Kauai receptions and compare the results to parabolic equation simulations. The results of this analysis will be used to develop random channel models for the low order modes and subsequently to develop new signal processing techniques for these modes.

The principal investigator for this project is Mr. Tarun K. Chandrayadula, a Ph.D. student in the Electrical and Computer Engineering Department at George Mason University. Mr. Chandrayadula's thesis advisor is Professor Kathleen E. Wage.

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14. ABSTRACT

The long term goals of this project are to investigate statistical models for signals propagating in long-range underwater channels and to design signal processing techniques to mitigate signal fluctuations due to random disturbances such as internal waves.

15. SUBJECT TERMS

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WORK COMPLETED

Since the start of this project in January 2006, work has focused on analysis of the LOAPEX and Kauai receptions from the 2004-2005 NPAL experiment.

Simulations: Parabolic Equation (PE) simulations modeling the range dependence of the statistics of the low order mode signals have been implemented. Statistics such as mean, mean envelope, temporal covariance and kurtosis have been estimated from simulations. Coupled mode simulations have been implemented to analyze the amplitude and phase statistics of the components of the signal that are unaffected by scattering. These results have been presented at the Acoustical Society of America (ASA) meeting in November 2006 [1], the NPAL workshop in May 2007, and the ASA meeting in June 2007 [2].

LOAPEX analysis: The signals received during LOAPEX were processed and analyzed. Statistics such as mean, mean envelope, and cross modal correlation at the different LOAPEX station were estimated to study the internal wave effects with respect to range.

Kauai analysis: The signals received during the 2004 NPAL experiment from the source deployed to the north of Kauai were processed and analyzed. Various statistics of the low order modes such as mean, variance, mean power, kurtosis, and skewness were estimated. The results of this analysis were presented at the NPAL Workshop in April 2006.

RESULTS

Modes exchange energy as they propagate through internal waves. At a given range, the signal in mode m consists of energy that has been scattered from other modes and an "unscattered component" that has propagated only in mode m. The unscattered component is not the same as the adiabatic component. The adiabatic model assumes that no scattering occurs, whereas the coupled mode model, which is used to compute the unscattered component, accounts for the exchange of energy among modes. A complete statistical model of the mode signals requires an understanding of the statistics of both the unscattered and scattered components.

In previous work, Dozier and Tappert estimated range-dependent statistics of the low order modes by making approximations to the coupled mode equations [3, 4]. Their seminal papers predict that the modes will have Gaussian statistics and that, at long enough ranges, energy will be partitioned equally among the modes. The simulations used to verify these predictions required significant approximations (due to computational limitations) that may not be valid in the real ocean. This project uses PE simulations, which are a more realistic means to study the range dependent statistics of modes. This project also uses coupled mode simulations to estimate the mean amplitude of the unscattered component as a function of range. In earlier work, Baggeroer and Scheer implemented an approximate form of PE simulations to study the amount of leakage from the unscattered component [5].

Parabolic equation simulations: A broadband PE simulation modeled internal wave effects at the different LOAPEX stations. The simulations assumed a broadband source at 800 m depth with a frequency range of 60 Hz to 90 Hz. Sound Speed Profiles (SSPs) along the LOAPEX path were extracted and averaged to obtain the background SSP. Random sound speed perturbations at a

Garrett-Munk strength of 0.5 were generated by the method of Colosi and Brown [6] and added to the mean sound speed profile to simulate internal wave effects. The PE simulation used the random sound speed profiles to simulate 100 different receptions for each of the seven LOAPEX stations. A broadband mode filter, as described in [7], processed the receptions to extract modes 1 to 10. The PE simulation used a one meter depth spacing to facilitate highly accurate mode filtering. The mode signals at the output of the beamformer were analyzed to estimate statistics such as mean envelope and kurtosis. This section discusses the estimated statistics and their variation with respect to range.

Kurtosis is a useful measure of the amount of scattering with respect to range. The kurtosis of a random variable is its fourth central moment divided by the square of the variance [8]. Since the kurtosis is always equal to 3 for a Gaussian random variable, it provides a useful test for Gaussianity. Dozier and Tappert [3] used the kurtosis measure to conclude that mode signals at megameter ranges are Gaussian-distributed. Figure 1 shows the estimated kurtosis for mode 1 signal at 75 Hz derived from the simulations. As the figure indicates, the kurtosis increases with respect to range and mode 1 approaches Gaussian statistics at approximately 1500 km. The increase in kurtosis with respect to range can be explained as follows. The kurtosis of a sum of random variables is greater than the kurtosis of each of the random variables [9]. Modes, due to scattering from internal waves, are effectively a sum of random contributions from other modes. The amount of random contributions increases across range due to cumulative internal wave effects, thus the kurtosis of the mode signal increases with respect to range. At megameter ranges, when the number of coupling events approaches infinity, the mode signal approaches Gaussian statistics by the central limit theorem [8]. Kurtosis curves estimated for frequencies other than 75 Hz showed that the kurtosis increases with increasing frequency, as expected, since coupling increases with frequency.

Estimates of the first and second order statistics such as mean, mean envelope and variance are functions of range. The mean time spread and variance increased with range. The cross correlation decreases to zero for ranges greater than 50 km. The results presented in this section imply that the complexity of the mode signal increases across range. Thus the mode signal thus cannot be represented by the same model at all ranges. An appropriate statistical model for the modes must vary with range, mode number, and frequency.

Coupled mode simulations: According to the coupled mode model, the mode signal $a_n^{(j+1)}$ at range segment $j+1$ due to internal waves is given by [10],

$$a_n^{(j+1)} = \sum_m C_{nm}^{(j)} a_m^{(j)}. \tag{1}$$

All equations in this section omit the $\dfrac{1}{\sqrt{r}}$ loss that occurs due to cylindrical spreading over a range r. To obtain an exact representation of the mode signal the expression for the coupling matrix in Equation 1 must be multiplied by the factor $\dfrac{1}{\sqrt{r}}$. The coupling matrix C_{nm}^{j} dictates the contribution from each mode. The coupling matrix is a random matrix that depends on the modeshapes Ψ_n and the wavenumbers k_n. The elements of the coupling matrix (*C*) are,

$$C^j_{nm} = e^{(ik^j_n \Delta r)} \frac{1}{2} \left(1 + \frac{k^j_m}{k^{j+1}_n}\right) \int_z \Psi^{j+1}_n(z) \Psi^j_m(z) dz. \tag{2}$$

The amplitude of the unscattered component is given by the elements along the main diagonal of the coupling matrix. For slow variations in sound speed such that the factor $\frac{k^j_m}{k^{(j+1)}_n} = 1$, the amplitude of the terms along the main diagonal for range segment j is

$$|c^j_{nn}| = \int_z \Psi^{(j+1)}_n(z) \Psi^{(j)}_n(z) dz. \tag{3}$$

Using Equation 3 and recursively applying Equation 1, the amplitude of the unscattered component at range segment $j+1$ is,

$$|a^{j+1}_n|_{unscattered} = \prod_{m=1}^{m=j} |c^m_{nn}|. \tag{4}$$

The phase of the unscattered component across range segment $j+1$ is given by

$$\angle a^{j+1}_{nn} = k^{j+1}_n \Delta r. \tag{5}$$

The modeshapes Ψ^j_n are of unit norm, thus $|c^j_{nn}| \leq 1$ for all j. This implies that the amplitude of the unscattered component should exponentially approach zero as j approaches infinity. However for small values of j, i.e., for shorter ranges, the amplitude of the unscattered component will be significant. With appropriate signal processing techniques this unscattered component should be detectable. The mean amplitude of the unscattered component provides an indication of the detectability of this feature.

To examine the statistics of the unscattered component, the SSPs that were generated for the PE simulations were used to calculate the modeshapes Ψ for every 1 km (assuming that the sound speed profiles remain roughly constant over a block size of 1 km). The amplitude of the unscattered component was calculated using Equation 3 and averaging over 100 realizations. Figure 2 shows the mean amplitude of the unscattered component for modes 1 to 10. The simulation confirms that the amplitude of the unscattered component decays across range. Mode 1 in Figure 2 has the slowest rate of decay and remains significant up to 400 km. Figure 3 shows the statistics of the mode wavenumbers at 75 Hz for modes 1, 5 and 10. The wavenumber of mode 1 is the most sensitive to internal wave effects. The time of arrival varies more than the time of arrival of the other modes. The average time spreads for mode 1 in experiments such as Acoustic Thermometry of Ocean Climate [11] and the Alternate Source Test [12] has been much higher than the time spreads observed for the ray arrivals. The high sensitivity of the phase of mode 1 to internal wave perturbations explains the comparatively high time spreads observed for mode 1. Figure 3 also shows that the mode wavenumbers are highly correlated across frequency. This implies that internal waves perturb the phase of the unscattered component but the different frequencies still constitute one coherent arrival. The net effect of the internal waves on the

unscattered component is to randomize the amplitude and to perturb the time of arrival. A simple model for the unscattered component in a broadband mode signal would be a signal with random amplitude that gets perturbed in time. The random amplitude and the random time of arrival would depend on the prevailing IW effects. Figure 2 shows that at shorter ranges (< 300 km) most of the mode signal is dominated by the unscattered component. Thus, at shorter ranges the mode signal should resemble the unscattered component. Figure 4 shows the results of PE simulation for mode 1 at 250 km. This simulation shows that mode 1 is dominated by a single arrival that wanders in time. Mode 1 in Figure 4 apparently fits the description of the model for the unscattered component. The results presented in this section are a function of the block size chosen for simulations. Further work is ongoing to determine an appropriate block size.

LOAPEX receptions: As part of LOAPEX, an acoustic source transmitted at ranges of 50 km, 250 km, 500 km, 1000 km, 1600 km, 2300 km and 3200 km to a 40 element vertical line array. The LOAPEX source transmitted pseudo random signals of bandwidth 30 Hz, from a depth of 800m and a carrier frequency of 75 Hz. The 75 Hz signals were complex demodulated and matched filtered. Figure 5 shows the mode 1 signal at 250 km. Figure 5 shows some faint arrivals preceding mode 1, which are due to cross talk from higher order modes. However the mode 1 signal is dominated by only a single arrival, which is mostly due to the unscattered component. The amount of time wander for the LOAPEX mode 1 signal in Figure 5 is less than the amount of time wander in the PE-simulated mode 1 signal in Figure 4. The difference in amounts of time wander can be explained as follows. The PE simulations modeled IW effects on mode signals by propagating the modes through different IW realizations. The simulated IW realizations are thus uncorrelated with each other and thus the time of arrival of mode 1 for a given realization is uncorrelated with the time of arrival from the preceding or the following IW simulation. LOAPEX transmissions occurred every hour. Since internal waves are correlated at lags of an hour, the mode 1 signals recorded during LOAPEX do not show the same amount of time wander as that of the PE simulations.

IMPACT/APPLICATIONS

This research has both scientific and operational applications. For applications such as tomography, it is important to quantify the effects of internal waves on travel times and other parameters that might be used in an inversion. Similarly, for source detection and localization problems, it is important to understand signal fluctuations in order to assess their impact on performance. For both applications, having a statistical model of propagation through internal waves is extremely important. This project is developing a model for the unscattered component of mode signals, as well as signal processing algorithms for detecting and estimating this component. Tracking the unscattered component will facilitate the use of low mode signals in tomographic inversions. Since the low modes are only excited by submerged sources, detecting this component enhances the ability of sonar systems to discriminate between surface and submerged sources.

RELATED PROJECTS

This work is closely related to the North Pacific Acoustic Laboratory project, directed by principal investigators Peter Worcester (Scripps) and James Mercer (APL - UW). Many other ONR-sponsored researchers work on projects related to NPAL and participate in the NPAL workshops.

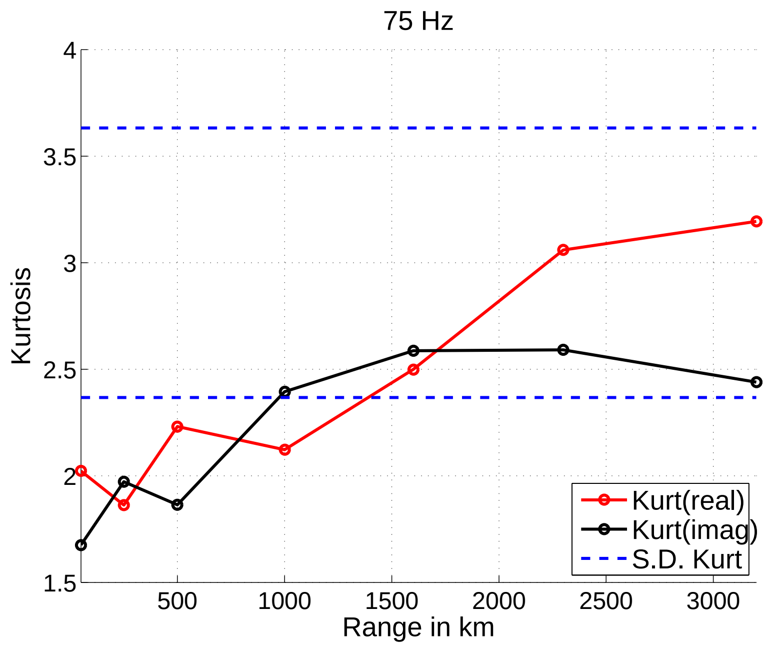

Figure 1: The kurtosis at 75 Hz at the different LOAPEX stations. The kurtosis calculations are based on 100 internal wave realizations. The dashed lines on the plot indicate the standard deviation for a 100 independent random variables assuming Gaussian statistics.

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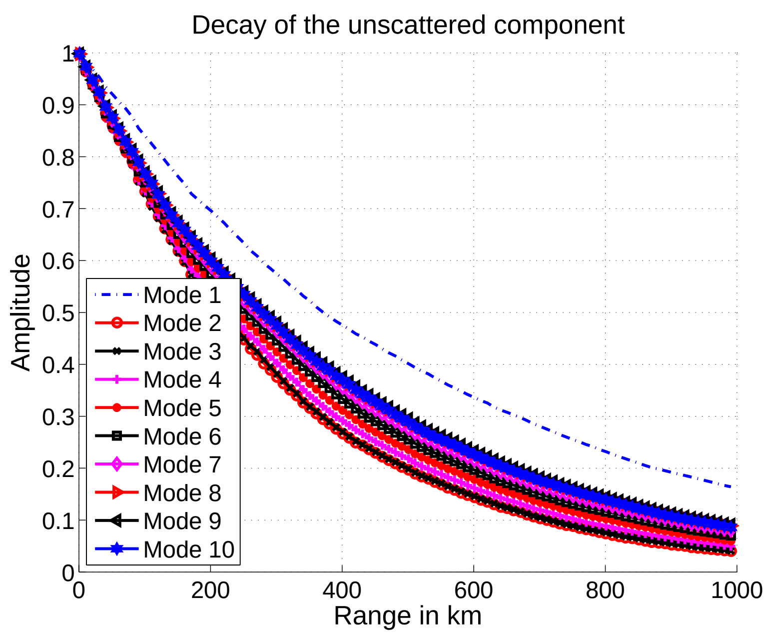

Figure 2: The amplitude of the unscattered component for modes 1 to 10 for ranges up to 1000 km. Modes 1 to 10 were initialized with an initial amplitude of 1 at the source. The unscattered component exponentially decays across range. Mode 1 is the slowest to decay. Note that the figure does not take into account cylindrical spreading losses for each mode.

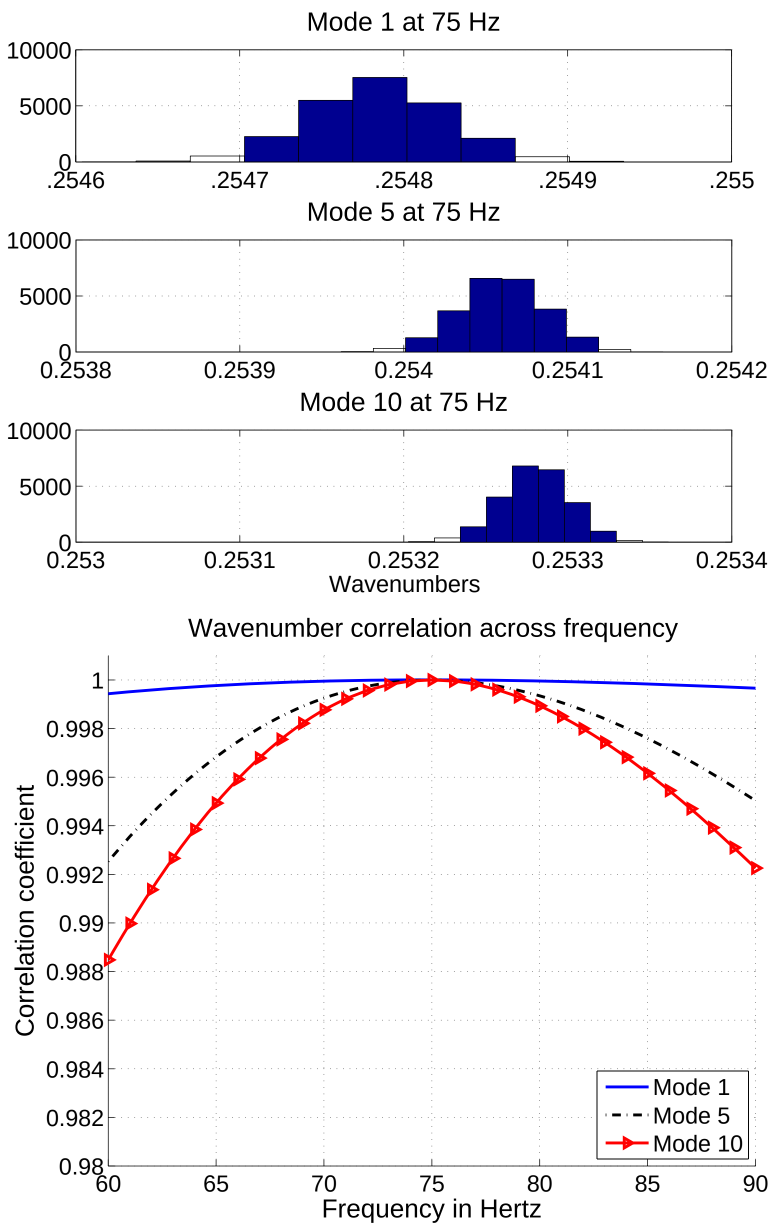

Figure 3: The plot on the top shows the histogram of the wavenumbers of modes 1, 5 and 10 at 75 Hz. The histograms were generated from wavenumbers calculated for a 1000 km range. The wavenumbers are Gaussian distributed. The plot at the bottom shows the correlation of the wavenumber at 75 Hz with wavenumbers at frequencies 60 Hz to 90 Hz. The wavenumbers are highly correlated across frequency.

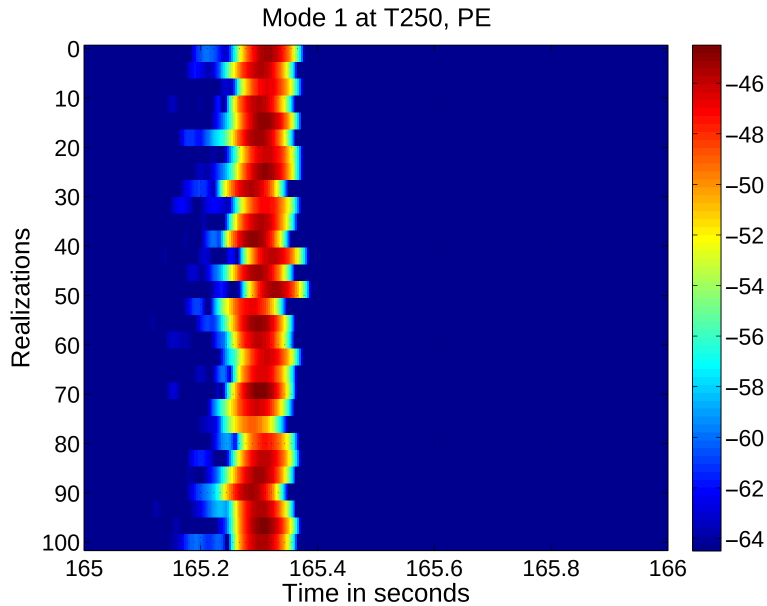

Figure 4: The mode 1 arrival at 250 km from PE simulations for 100 IW realizations. The mode 1 signal consists of a single arrival. At 250 km mode 1 consists of a single arrival that wanders in time due to internal wave perturbations.

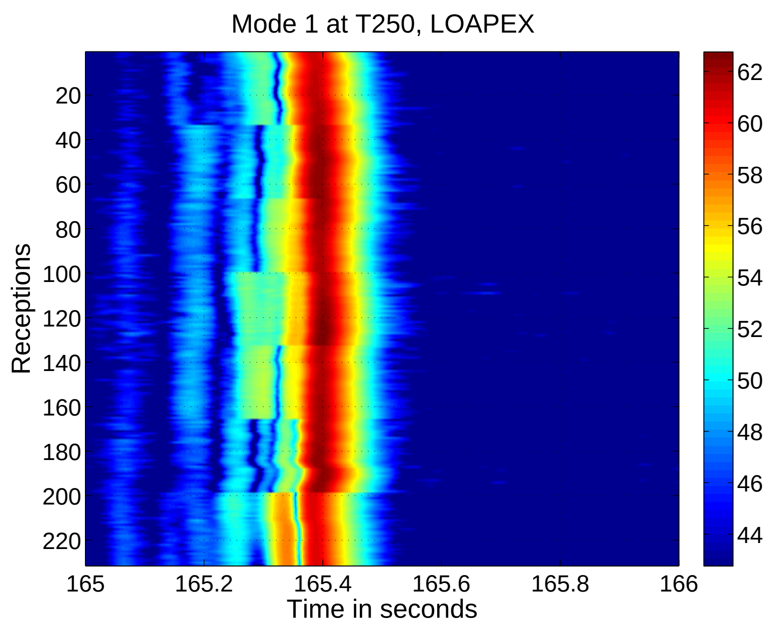

Figure 5: The mode 1 signal recorded at station T250 during LOAPEX. At 250 km range, the measures mode 1 is dominated by a single arrival. Mode 1 has a few faint arrivals preceeding it. The faint arrivals are due to crosstalk from higher order modes.